

Electromagnetic form factors of the nucleon in the chiral constituent quark model

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Abstract.

The electromagnetic form factors have attracted lot of theoretical and experimental attention recently as they encode extensive information on the internal structure of the hadron. An understanding of the form factors is necessary to describe the strong interactions as they are sensitive to the pion cloud and provide a test for the QCD inspired effective field theories based on the chiral symmetry. In view of the very exciting recent developments in the field, we propose to apply the techniques of chiral constituent quark model to measure the electromagnetic form factors of the nucleon. The results obtained are comparable to the latest experimental studies and also show improvement over some theoretical interpretations.

Keywords: Electromagnetic form factors, chiral Lagrangian

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INTRODUCTION

The knowledge of internal structure of nucleon in terms of quark and gluon degrees of freedom in QCD provides a basis for understanding more complex, strongly interacting matter. The electromagnetic form factors are the fundamental quantities of theoretical and experimental interest to investigate the internal structure of nucleon. Recently, a wide variety of accurately measured data have been accumulated for the static properties of baryons, for example, masses, electromagnetic moments, charge radii etc.. which are important as they lie in the nonperturbative regime of QCD. While QCD is accepted as the fundamental theory of strong interactions, it cannot be solved accurately in the nonperturbative regime. A coherent understanding of the hadron structure in this energy regime is necessary to describe the strong interactions as they are sensitive to the pion cloud and provide a test for the QCD inspired effective field theories based on the chiral symmetry. A promising approach is offered by constituent-quark models which can be modified to include the relevant properties of QCD in the nonperturbative regime, notably the consequences of the spontaneous breaking of chiral symmetry (χ SB).

ELECTROMAGNETIC FORM FACTORS

The internal structure of nucleon is determined in terms of electromagnetic Dirac and Pauli form factors $F_1(Q^2)$ and $F_2(Q^2)$ or equivalently in terms of the electric and magnetic Sachs form factors $G_E(Q^2)$ and $G_M(Q^2)$ [1]. The issue of determination of the form factors has been revisited in the recent past with several new experiments

measuring the form factors with precision at MAMI [2] and JLAB [3] which are in significant disagreement with those obtained from the Rosenbluth separation [4]. This inconsistency leads to a large uncertainty in our knowledge of the proton electromagnetic form factors and urge the necessity for the new parameterizations and analysis [5].

The most general form of the hadronic current for a spin $\frac{1}{2}$ -nucleon with internal structure is given as

$$\langle B | J_{\text{had}}^\mu(0) | B \rangle = \bar{u}(p') \left(\gamma^\mu F_1(Q^2) + i \frac{\sigma^{\mu\nu}}{2M} q_\nu F_2(Q^2) \right) u(p), \quad (1)$$

where $u(p)$ and $u(p')$ are the 4-spinors of the nucleon in the initial and final states respectively. The Sachs form factors G_E and G_M can be related to the Dirac and Pauli form factors and the Fourier transform can be expressed in terms of the nucleon charge density. The most general form of the multipole expansion in the spin-flavor space is

$$A' \sum_{i=1}^3 e_i \mathbf{1} - B' \sum_{i \neq j}^3 e_i \left[2\sigma_i \cdot \sigma_j - (3\sigma_{iz}\sigma_{jz} - \sigma_i \cdot \sigma_j) \right] - C' \sum_{i \neq j \neq k}^3 e_i \left[2\sigma_j \cdot \sigma_k - (3\sigma_{jz}\sigma_{kz} - \sigma_j \cdot \sigma_k) \right]. \quad (2)$$

The charge radii operator composed of one-, two-, and three-quark terms is expressed as

$$\widehat{r^2} = A \sum_{i=1}^3 e_i \mathbf{1} + B \sum_{i \neq j}^3 e_i \sigma_i \cdot \sigma_j + C \sum_{i \neq j \neq k}^3 e_i \sigma_j \cdot \sigma_k,$$

whereas the quadrupole moment operator can be expressed as

$$\widehat{Q} = B' \sum_{i \neq j}^3 e_i (3\sigma_{iz}\sigma_{jz} - \sigma_i \cdot \sigma_j) + C' \sum_{i \neq j \neq k}^3 e_i (3\sigma_{jz}\sigma_{kz} - \sigma_j \cdot \sigma_k).$$

The coefficients $A = A'$, $B = -2B'$, and $C = -2C'$ are the general parameterization (GP) method parameters [6, 7].

CHARGE RADII

The mean square charge radius (r_B^2), giving the possible “size” of baryon, has been investigated experimentally with the advent of new facilities at JLAB, SELEX Collaborations [8, 9]. Several measurements have been made for the charge radii of p , n , and Σ^- in electron-baryon scattering experiments [10, 11] giving $r_p = 0.877 \pm 0.007$ fm ($r_p^2 = 0.779 \pm 0.025$ fm² [12]) and $r_n^2 = -0.1161 \pm 0.0022$ fm² [9].

The charge radii operators for the spin $\frac{1}{2}^+$ octet and spin $\frac{3}{2}^+$ decuplet baryons can be expressed in terms of the flavor ($\sum_i e_i$) and spin ($\sum_i e_i \sigma_{iz}$) structure of a given baryon as

$$\widehat{r_B^2} = (A - 3B) \sum_i e_i + 3(B - C) \sum_i e_i \sigma_{iz}, \quad (3)$$

$$\widehat{r_{B^*}^2} = (A - 3B + 6C) \sum_i e_i + 5(B - C) \sum_i e_i \sigma_{iz}. \quad (4)$$

It is clear from the above equations that the determination of charge radii basically reduces to the evaluation of the . The charge radii squared $r_{B(B^*)}^2$ for the octet (decuplet) baryons can now be calculated by evaluating matrix elements corresponding to the operators in Eqs. (3) and (4) and are given as $r_B^2 = \langle B | \hat{r}_B^2 | B \rangle$, $r_{B^*}^2 = \langle B^* | \hat{r}_{B^*}^2 | B^* \rangle$. Here, $|B\rangle$ and $|B^*\rangle$ respectively, denote the spin-flavor wavefunctions for the spin $\frac{1}{2}^+$ octet and the spin $\frac{3}{2}^+$ decuplet baryons.

The naïve quark model (NQM) [13] calculations show that the results are in disagreement with the available experimental data. In this context, the chiral constituent quark model (χ CQM) [14, 15], which incorporates chiral symmetry breaking, has been extended to calculate the charge radii of spin $\frac{1}{2}^+$ octet and spin $\frac{3}{2}^+$ decuplet baryons using GP method. A redistribution of flavor and spin takes place among the “sea quarks” in the interior of hadron due to the fluctuation process and chiral symmetry breaking in the χ CQM. The most significant prediction of the model is the non-zero value pertaining to the charge radii of the neutral octet baryons (n , Σ^0 , Ξ^0 , and Λ) and decuplet baryons (Δ^0 , Σ^{*0} , Ξ^{*0}). The effects of SU(3) symmetry breaking have also been investigated and the results show considerable improvement over the SU(3) symmetric case. New experiments aimed at measuring the charge radii of the other baryons are needed for a profound understanding of the hadron structure in the nonperturbative regime of QCD.

QUADRUPOLE MOMENTS

Recent experimental developments [16, 17], providing information on the radial variation of the charge and magnetization densities of the proton, give the evidence for a deviation of the charge distribution from spherical symmetry. Since the quadrupole moment of the nucleon should vanish on account of its spin-1/2 nature, this observation has naturally turned to be the subject of intense theoretical and experimental activity. In this context, $\Delta(1232)$ resonance being the lowest-lying excited state of the nucleon, plays a very important role in the low energy baryon phenomenology.

The spin and parity selection rules in the $\gamma + p \rightarrow \Delta^+$ transition allow three contributing amplitudes, the magnetic dipole G_{M1} , the electric quadrupole moment G_{E2} , and the charge quadrupole moment G_{C2} photon absorption amplitudes [18, 19]. The G_{M1} amplitude gives us information on magnetic moment whereas the information on the intrinsic quadrupole moment can be obtained from the measurements of G_{E2} and G_{C2} amplitudes [9]. If the charge distribution of the initial and final three-quark states were spherically symmetric, the G_{E2} and G_{C2} amplitudes of the multipole expansion would be zero [21]. However, recent results on non-zero quadrupole amplitudes [8, 20] lead to the conclusion that the nucleon and the Δ^+ are *intrinsically* deformed.

For the case of octet baryons we find that the quadrupole moments are zero for all the cases in NQM. In the SU(3) symmetry breaking limit, the “small” numeric value of quadrupole moment measures the deviation in shape of baryons from the spherical symmetry. The predicted signs of *intrinsic* quadrupole moment are important as they measure the type of deformation in the baryon. The small observed negative value of p and n quadrupole moments suggest that these are oblate in shape which is in agreement with several other calculations in literature.

For the case of decuplet baryons, the quadrupole moments of the charged baryons are equal whereas all neutral baryons have zero quadrupole moment. The results in NQM using the GP method predict an oblate shape for all positively charged baryons (Δ^{++} , Δ^+ , and Σ^{*+}), prolate shape for negatively charged baryons (Δ^- , Σ^{*-} , Ξ^{*-} , and Ω^-). On incorporating the effects of chiral symmetry breaking and “quark sea” in the χ CQM, a small amount of prolate deformation in neutral baryons (Δ^0 , Σ^{*0} , and Ξ^{*0}) is observed.

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